FINAL REPORT

to

Office of Naval Research

under

Contract N00014-77 C-0265

from 1989

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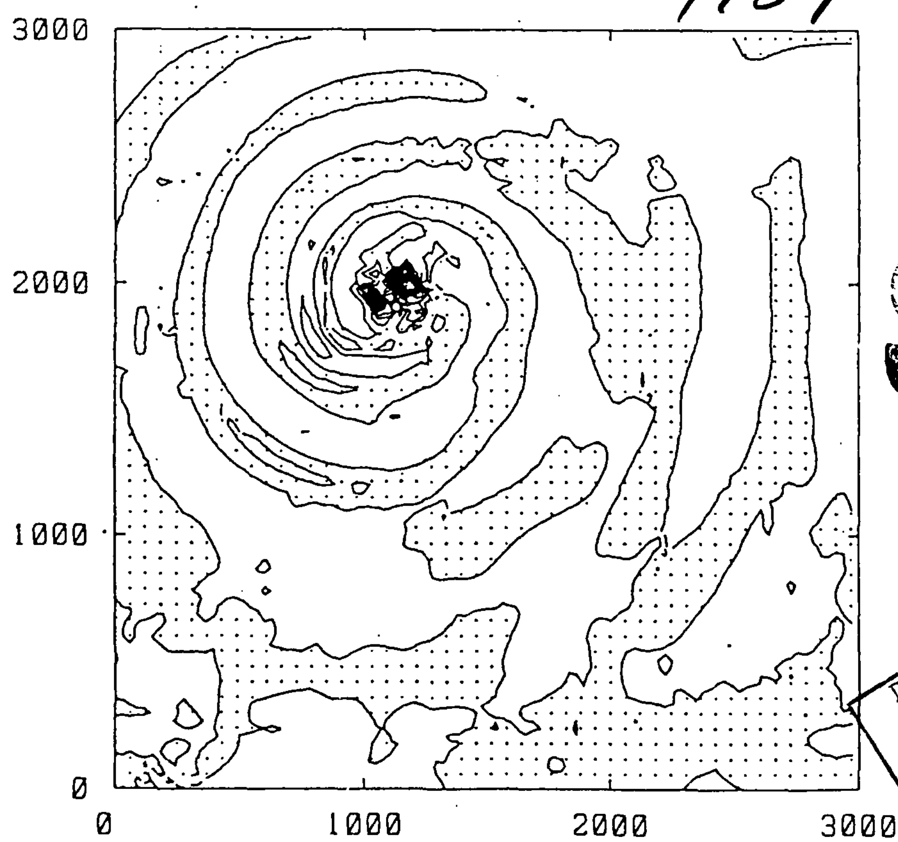
D3 TIME= 50. HRS VERTICAL VELOCITY

1989



NEGATIVE SHADING

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Summary of Accomplishments

Under ONR Contract N00014–75C–0265 we published 22 scientific papers in quality journals with high standards of review describing our accomplishments in three major areas: A. The mechanism of hurricane formation, B. Diagnostic studies of wave-mean flow interactions in the atmosphere and C. Laboratory simulations of fundamental atmospheric processes.

A. The Mechanism of Hurricane Formation

In a series of 5 papers, we have confirmed the hypothesis that large-scale eddy fluxes of momentum associated with upper-level asymmetries in the wind field play a fundamental role in hurricane formation. They do this by inducing the radial circulation which draws warm, moist lower tropospheric air inward toward the center of the disturbance over a large fetch of ocean and pumps drier air out at higher elevations. In the studies by Challa and Pfeffer (1980) and Pfeffer and Challa (1981, 1982) we used Sundqvist's (*Tellus*, **22**, 369–390, 1970) symmetric hurricane model, modified to include parameterized eddy fluxes of momentum, to investigate the role of such fluxes in hurricane formation.

The first paper reported the results of a sensitivity study in which the model was integrated with various prescribed distributions of the eddy momentum flux and sea-surface temperature. It was found that a model hurricane developed in every numerical integration in which an eddy momentum flux *convergence* was specified, and that hurricane development was suppressed when an eddy momentum flux *divergence* was prescribed. The authors also used the diagnostic vertical circulation equation developed by Eliassen (*Astrophys. Norv.*, **5**, 19–60, 1952) and Kuo (*J. Meteor.*, **13**, 561–568, 1956) to discuss the mechanism by which the eddy fluxes of momentum induce the radial circulation and showed which distributions were more favorable for rapid hurricane development.

In the second paper, the authors described the results of similar numerical integrations of Sundqvist's model in which the somewhat arbitrary specifications of momentum flux and initial

vortex strength used in the sensitivity study were replaced with data from composites of many tropical disturbances. The momentum flux data and the initial tangential wind and moisture distributions were taken from the composite data analyses of developing (prehurricane) and non-developing tropical disturbances prepared by McBride (*J. Atmos. Sci.*, **38**, 1117–1131 and 1152–1166, 1981) and McBride and Zehr (*J. Atmos. Sci.*, **38** 1132–1151, 1981). Pfeffer and Challa (1981) combined the data from Atlantic prehurricane cloud clusters, depressions and intensifying cyclones into a composite Atlantic developing disturbance, and the data from non-developing cloud clusters, wave trough clusters and depressions into a composite Atlantic non-developing disturbance. The composite for the developing disturbance revealed a large, well-organized, inward eddy flux of momentum centered around 200 mb, increasing radially outward from 6° to 14° lat from the center of the disturbance. In the non-developing case, there was a rather weak momentum flux maximum at a radius of 10° lat. Numerical integrations were performed using the data for both cases with the observed distributions of the eddy flux of angular momentum. A further integration was performed using the initial tangential wind and moisture distribution corresponding to the developing disturbance, but with the eddy flux of momentum set to zero everywhere. The initial vortex associated with the developing disturbance intensified rapidly and reached hurricane strength within 4 days, whereas the vortex associated with the non-developing disturbance failed to intensify beyond a 10 m s^{-1} maximum tangential wind after 10 days, at which point the integration was terminated. With the eddy flux of momentum set to zero, the initial vortex associated with the developing disturbance also failed to intensify beyond 10 m s^{-1} after 16 days.

In the study by Pfeffer and Challa (1982), additional numerical integrations of Sundqvist's model were made with and without the observed eddy fluxes of momentum corresponding to the individual prehurricane cloud cluster, depression and intensifying cyclone defined by McBride's original dataset without further compositing. With the observed eddy flux forcing, all three initial vortices intensified rapidly into hurricanes. The rates of growth, the final intensities, eye structures

and sizes of the resulting model hurricanes, were found to be sensitive to the details of the eddy momentum flux distribution. Without eddy flux forcing, both the prehurricane cloud cluster and the prehurricane depression failed to develop into a hurricane after 16 days of integration, and the intensifying cyclone required approximately 13 days to reach hurricane strength.

The results of our integrations with Sundqvist's model suggest that the presence of a sufficiently intense, properly organized, eddy flux convergence of momentum may be a necessary ingredient for the development of Atlantic tropical disturbances into hurricanes. We were gratified to see this hypothesis confirmed independently in an observational study of hurricane Elena (1985) by Mollinari and Vollaro (*J. Atmos. Sci.*, in press). These investigators found a high correlation, with a lag of 27–33 hours, between fluctuations of the eddy momentum flux convergence at large radii in the outflow layer of hurricane Elena and fluctuations of the central pressure of the storm.

The role of the eddy momentum flux convergence is to induce the radial circulation which brings warm, moist air into a central location, thereby concentrating the release of latent heat of condensation. The results of Pfeffer and Challa's numerical studies with Sundqvist's model suggest that (i) the initial vortex, at least in cloud clusters and depressions which later develop into hurricanes, is too weak to intensify into a hurricane through the action of Ekman pumping and cooperative instability alone and that (ii) the eddy fluxes of momentum associated with tropical disturbances that do not develop into hurricanes in nature are too weak and diffuse to organize the radial circulation and the resulting influx of moisture in the lower troposphere needed to fuel the growth of a hurricane.

These results cannot, however, be considered conclusive because they were based on the use of an axially-symmetric hurricane model with parameterized eddy fluxes of momentum. Accordingly, a new study was undertaken by Challa et al. (1989) in which these constraints were removed by using the fully 3-dimensional Naval Research Laboratory operational hurricane model of Madala et al. (NRL Memorandum Report 5992). The initial conditions for these integrations were extracted

from analyzed charts prepared at FSU by Professor Noel LaSeur from McBride's tabulations by octant and radius. Numerical integrations were performed using the data for the developing and non-developing cloud cluster and depression as initial conditions. Moreover, two additional integrations were performed for comparison in which the eddy fluxes of momentum were removed by using as initial conditions only the axially-symmetric components of the wind and moisture fields in the developing cloud cluster and depression. In these integrations, the prehurricane cloud cluster with the eddy fluxes of momentum removed did not grow even after 90 hours of integration, whereas, with the eddy fluxes included in the initial conditions, it developed gale force winds by 13 hours and hurricane winds by 40 hours. The minimum surface pressure reached 991.5 mb at 60 hours and the maximum wind speed reached 44 m s^{-1} at 70 hours. The maximum winds in the prehurricane depression reached 14 m s^{-1} at 75 hours with the eddy fluxes removed and 46 m s^{-1} at 70 hours with the eddy fluxes included in the initial conditions. In the latter case the minimum surface pressure reached 989.1 mb. Similar integrations with the NRL operational hurricane model using initial conditions corresponding to cloud clusters and depressions which did not develop in nature showed that the observed eddy fluxes of momentum in these situation were not strong enough, or well-enough organized, to permit these disturbances to develop into hurricanes. In these cases there was no intensification of the disturbance after 60 hours, at which time each of the integrations was terminated.

Suggestions for Future Research:

In recent years, there has become available, largely through the auspices of ECWMF, a wealth of 4-dimensionally initialized global data from which initial conditions can be extracted for the purpose of making forecasts of the development and motion of individual hurricanes and typhoons which formed all over the world in each year since 1979. We are convinced that the process we have isolated in connection with the development of hurricanes is also at work in determining the

motion of hurricanes. We feel that the time is ripe to test this hypothesis with a series of numerical integrations corresponding to individual hurricanes and typhoons, carrying these integrations from the incipient stages through the entire life cycle of each disturbance. With the model and data we have at hand, and the supercomputers available to us, we are prepared to conduct such studies. We can do this, however, only if we receive further support for such research.

B. Wave-Mean Flow Interactions in the Atmosphere

Our application of conventional and transformed Eulerian diagnostics to the study of fluctuations of the zonal mean jet has been reported in two published papers (Pfeffer, 1981, 1987), an Atlas of FGGE diagnostics (Pfeffer and Lu, 1989) and three presentations by Professor Pfeffer (National Academy of Science FGGE Workshop, 1984; NASA Goddard Seminar, 1985; and National Conference on FGGE, 1986). These studies provide convincing evidence to support the hypothesis that the zonal mean jet responds much more sensitively to eddy fluxes of momentum, which appear explicitly in the conventional Eulerian momentum equation, than to eddy fluxes of heat, which provide the dominant contribution to the eddy force in the transformed Eulerian momentum equation. In order to appreciate the significance of this conclusion, and its implications to medium range weather forecasting, it is necessary to view it in light of the following background.

Transformed Eulerian diagnostics, which has gained much currency in recent years due to the work of Andrews and McIntyre (*J. Atmos. Sci.*, **33**, 2031–2048, 1976) and Edmon, Hoskins and McIntyre (*J. Atmos. Sci.*, **37**, 2600–2616, 1980), is based on the discovery by Eliassen and Palm (*Geophys. Publ.*, **22**, 1–23, 1960) and Charney and Drazin (J. Geophys. Res., **66**, 83–109) of a vector, **F**, now called the Eliassen-Palm (E-P) flux, whose divergence is a measure of the net eddy force exerted on the zonal mean flow, $\overline{u}$. The E-P flux vector points in the direction of energy propagation of the waves. Its meridional component is proportional to the negative of the poleward eddy flux of momentum, and its vertical component is proportional to the poleward

eddy flux of heat. Plots of this vector reveal that Rossby waves generally propagate upward in the mid-latitude troposphere and equatorward in the upper troposphere and lower stratosphere, and that they dissipate in the tropics. On occasions, the waves break through the tropopause, traveling deep into the stratosphere where they turn poleward and focus their energy in the polar night jet, causing sudden stratospheric warmings and catastrophic reversals of this jet.

In conventional Eulerian diagnostics, the zonal momentum equation may be written to lowest order in the form

$$\frac{\partial \overline{u}}{\partial t} = f\overline{v} - \frac{1}{r\cos\phi}\nabla\cdot\mathbf{M} - D, \tag{1}$$

where $\overline{u}$ and $\overline{v}$ are the zonal mean zonal and meridional components of velocity, $\mathbf{M}$ is the eddy flux of angular momentum, ϕ is latitude, f the Coriolis parameter and D the dissipation. In this equation, the eddy force on the mean flow is represented by the eddy flux convergence of momentum and the Coriolis force reflects the action of mean meridional circulations such as the Hadley and Ferrel cells. In transformed Eulerian diagnostics, the same equation is transformed into the form

$$\frac{\partial \overline{u}}{\partial t} = f\overline{v}^* + \frac{1}{r\cos\phi}\nabla\cdot\mathbf{F} - D. \tag{2}$$

Here, the eddy force is represented by the divergence of the E-P flux, $\mathbf{F}$, and the Coriolis force reflects the action of the "residual" meridional circulation, $\overline{v}^*$. For small amplitude disturbances the residual circulation is closely related to, but not identical to, the Lagrangian mean meridional circulation.

As a result of the work of Andrews and Edmon et al. (loc. cit.), a view has emerged in recent years that fluctuations of the zonal mean flow should correlate much better with $\nabla\cdot\mathbf{F}$ in the transformed momentum equation than with $-\nabla\cdot\mathbf{M}$ in the conventional momentum equation because the E-P flux incorporates both the eddy heat and momentum fluxes and represents the *net* eddy force on the zonal mean flow. On average, this force is found to be negative in the mid-latitude troposphere, implying deceleration. Our research has demonstrated, however, that the zonal mean

jet does not respond directly to the net eddy force. Rather, a substantial portion of this force is consumed in driving the residual mean meridional circulation which exerts an almost equal and oppositely directed Coriolis force on the zonal mean jet. As a result, the fluctuations of the zonal mean jet are measured as small differences between two large and oppositely directed quantities (viz., $\nabla \cdot \mathbf{F}$ and $f\overline{v}^*$) in equation (2). On the other hand, our studies reveal that $\partial\overline{u}/\partial t$ correlates well with $-\nabla \cdot \mathbf{M}$ in equation (1), such that the eddy flux convergence of momentum accounts for about 50% of the variance of the fluctuations of the zonal mean jet. In a related study, we found that a defect of the standard resolution NASA GLA general circulation model, which results in the deterioration of its predictions over periods of the order of 5 days or more, is its inability to retain accuracy in the poleward eddy flux of momentum.

In a separate study, Lu and Pfeffer (1985) developed a spectral iterative method for solving the meridional circulation equation in spherical sigma coordinates in which the moist static stability is retained (instead of replacing it by the dry static stability) and the equation is hyperbolic over the tropics. Prior to this work, all methods of solving this equation required replacing the moist static stability with the dry static stability in order to stabilize the integration by making the equation elliptic everywhere. A reprint of this paper together with all the others is included with this Final Report.

C. Laboratory Simulations of Atmospheric Processes

In 14 papers published in major scientific journals we have reported on the results of an extensive series of laboratory experiments and related theory of baroclinic flows designed to test various hypotheses. These experiments were performed in thermally-driven rotating fluids over a broad parameter range, with and without bottom topography. Controlled laboratory experiments have long been recognized as a valuable tool for isolating fundamental processes responsible for atmospheric behavior and testing theoretical hypotheses concerning the mechanisms involved. In

such experiments the external influences on the system can be varied like a rheostat and long term statistics and responses can be generated and measured for very small fractions of the cost of field experiments. A great strength of the experimental models lies in their simplicity and the fact that they truly model the essential mechanisms underlying atmospheric behavior. An important aspect of our work has been the development and deployment of synoptic networks of up to 2040 probes which measure the *field distribution* of temperature and velocity in the fluid as a function of time. The use of such networks has, in fact, been a unique characteristic of our laboratory, accomplished only with the steady support of ONR over a number of years. The following is a very brief summary of our published papers, some of which are rather comprehensive treatments of the subject:

Lacher, McArthur and Buzyna (1977) explored whether the observed time-dependent behavior in our experimental flows could be described by catastrophe theory. They found that it could and they developed a cusp model to describe an important class of flows. Buzyna, Pfeffer and Kung (1978) tested whether purely cyclic ("seasonal") variations of the imposed temperature contrast could result in anomalous behavior. They found that, under conditions very similar to those which characterize the earth's atmosphere, anomalous winters and summers developed in spite of the fact that no anomalous forcing was present. They attributed this to nonlinearity which impresses on the system a memory of its recent past as it enters a new season. This memory can cause the atmosphere to respond differently in different years to the same seasonal forcing. Extrapolating from the results of the experiments, it is reasonable to conclude that anomalous sea surface temperatures or solar output are not required to explain anomalous atmospheric behavior.

Pfeffer and Barcilon (1978) and Barcilon and Pfeffer (1979) used nonlinear theory to test whether poleward eddy heat fluxes in meteorological flows could legitimately be parameterized as being directly proportional to the meridional temperature gradient, as is often done in the literature. They found that there are fundamental reasons why such parameterizations are incorrect. They also found that the poleward eddy heat flux increases with decreasing Rossby number near

marginal stability, with significant drops at certain critical points, which Barcilon later related to observed changes in atmospheric behavior. These theoretical results were confirmed by the extensive experiments of Pfeffer, Buzyna and Kung (1980b) who also found a negative time correlation between the poleward eddy heat flux and the meridional temperature gradient. These investigators explained this result on the basis of the eddy feedback on the zonal temperature field. In two other papers, Pfeffer, Buzyna and Kung (1980a) and Buzyna, Pfeffer and Kung (1989) isolated different types of vacillation in rotating laboratory experiments which are similar to atmospheric vacillations reported in the literature and discussed their characteristics.

In a major work, Buzyna, Pfeffer and Kung (1984) tested the hypothesis that geostrophic turbulence is manifested by a minus three power slope of energy vs. wave number at the high wave number end of the spectrum. They found that the slope was by no means constant as they traversed dimensionless-parameter space. Instead, there is a systematic decrease of the slope with increasing Rossby number from about -5 at the onset of geostrophic turbulence to about -2 deep inside the turbulence regime. If one examines atmospheric data carefully in light of this work, one finds different slopes in winter and summer data which is consistent with the experiments since the atmospheric Rossby number is greater in winter than in summer. These results point to the need for a new theory of geostrophic turbulence to replace the pioneering work of Charney (*J. Atmos. Sci.*, **20**, 1087–1095, 1971). The techniques of making synoptic temperature and velocity measurements with networks of thermistor anemometers used in these various experiments were described in a paper by Kung, Buzyna and Pfeffer (1987).

In recent years, we have turned our attention to the study of baroclinic flows in the presence of bottom topography. Since the largest single component of an east-west Fourier analysis of the earth's mountains in the Northern Hemisphere middle latitudes is wave number 2, the first such experiments have been conducted in a rotating annulus with 2-wave bottom topography. Li, Kung and Pfeffer (1986, 1987, 1988) found that the effect of such bottom topography is to modulate

the synoptic-scale waves in both space and time, suppress the odd modes and force a "planetary" scale mode which oscillates about a climatological mean position with high pressure centers located upstream of the mountain ridges. Pfeffer, Kung and Li (1989) applied linear barotropic and baroclinic theory to explain a systematic shift of the high pressure center to the west with increasing Rossby number. Their theory gave qualitatively the same results as the experiments, but showed significant quantitative differences which will require nonlinear theory to explain. Their theoretical approach was similar to that used by meteorologists (see Held, *Large-Scale Dynamical Processes in the Atmosphere*, ed. B. Hoskins and R. Pearce, Academia Press, 127–167, 1983) to account for stationary waves in the atmosphere. By adjusting the magnitude of the atmospheric eddy diffusion coefficient, about which little is known, meteorologists can tune the theory to fit the data. Since we do not enjoy such luxury in the case of the experiments, because the diffusion coefficient is a known property of the fluid, we must accept the discrepancies as real and move on to treat the nonlinear problem. The implication of this work is that the theory of atmospheric stationary waves also requires such a nonlinear treatment. In another study of flow over topography, Pfeffer, Ahlquist, Kung, Chang and Li (1989) applied complex principal component analysis to experimental data in order to ascertain the nature of the modulation of baroclinic waves due to topography. Their analysis revealed two classes of wave behavior. One is resonant, in which the wave behavior downstream of the two topographic peaks is similar. The waves speed up and diminish in intensity as they traverse the topographic peaks and slow down and intensify downstream of the peaks. In the other type of behavior, the waves downstream of one mountain are unrelated to those downstream of the other mountain. This non-resonant behavior is vividly displayed by the principal component analysis.

Suggestions for Future Research:

We feel there is much to be done in laboratory experiments in the future. Among other things,

flows over mountains with different shapes need to be studied and land sea heating differences need to be explored. Moreover, seasonal variations should be imposed in experiments with mountains and land sea heating differences. Further support is required to accomplish these goals.

Acknowledgments

The accomplishments described in the preceding sections would not have been possible without the steady support of the Office of Naval Research over a period of years. We are deeply grateful, in particular, to Dr. James Hughes who was always supportive of new ideas and who never lost sight of the long standing, enlightened ONR philosophy of research support, basing his judgement of our research accomplishments on published papers and requiring a minimum of report and proposal writing.

References to Papers Published

Under ONR Conract N00014-75C-0265

A. Hurricane Formation

Challa, M. and R. L. Pfeffer, 1980: Effects of eddy fluxes of angular momentum on model hurricane development. *J. Atmos. Sci.*, **37**, 1603-1618.

Pfeffer, R. L. and M. Challa, 1981: A numerical study of the role of eddy fluxes of momentum in the development of Atlantic hurricanes. *J. Atmos. Sci.*, **38**, 2393-2398.

Pfeffer, R. L. and M. Challa, 1982: Model development of Atlantic hurricanes from prehurricane cloud clusters, depressions and cyclones. *Topics in Atmospheric and Oceanographic Sciences*, ed. Bengtsson/Lighthill, Springer-Verlag, 81-94.

Challa, M. and R. L. Pfeffer, 1984: The effect of cumulus momentum mixing on the development of a symmetric model hurricane. *J. Atmos. Sci.*, **41**, 1312-1319.

Challa, M. and R. L. Pfeffer, 1989: The formation of Atlantic hurricanes from cloud clusters and depressions. Submitted to *J. Atmos. Sci.*, April.

B. Diagnostic studies of wave-mean flow interaction

Pfeffer, R. L., 1981: Wave-mean flow interactions in the atmosphere. *J. Atmos. Sci.*, **38**, 1340-1359.

Pfeffer, R. L., 1984: Review of research on wave-mean flow interactions using FGGE data. *Proceedings* of the National Academy of Science FGGE Workshop, July.

Lu, H. I. and R. L. Pfeffer, 1985: Application of the spectral method to solve the meridional circulation equation in spherical sigma coordinates. *Mo. Wea. Rev.*, **113**, 1868-1875.

Pfeffer, R. L., 1987: Comparison of conventional and transformed Eulerian diagnostics. *Quart. J. Roy. Met. Soc.*, **113**, 237-254.

Pfeffer, R. L., 1989: An atlas of FGGE diagnostics. FSU publication.

C. Experimental Studies

Lacher, R. C., R. McArthur and G. Buzyna, 1977: Catastrophic changes in circulation flow patterns. *American Scientist*, **65**, 614-621.

Pfeffer, R. L., and A. Barcilon, 1978: Determination of eddy fluxes of heat and eddy temperature variances using weakly nonlinear theory. *J. Atmos. Sci.*, **35**, 2099-2110.

Buzyna, Pfeffer and Kung, 1978: Cyclic variations of the imposed temperature contrast in a thermally driven rotating annulus of fluid. *J. Atmos. Sci.*, **35**, 859-881.

Barcilon, A., and R. L. Pfeffer, 1979: Further calculations of eddy heat fluxes and temperature variances in baroclinic waves using weakly nonlinear theory. *Geophys. Astrophys. Fluid Dyn.*, **12**, 45-60.

Pfeffer, R. L., G. Buzyna and R. Kung, 1980a: Time-dependent modes of behavior of thermally-driven rotating fluids. *J. Atmos. Sci.*, **37**, 2129-2149.

Pfeffer, R. L., G. Buzyna and R. Kung, 1980b: Relationships among eddy fluxes of heat, eddy temperature variances and basic-state temperature parameters in thermally-driven rotating fluids. *J. Atmos. Sci.*, **37**, 2577–2599.

Buzyna, G., R. L. Pfeffer and R. Kung, 1984: Transition to geostrophic turbulence in a rotating differentially-heated annulus of fluid. *J. Fluid Mech.*, **145**, 377–403.

Li, G. Q., R. Kung and R. Pfeffer, 1986: An experimental study of baroclinic flows with and without two-wave bottom topography. *J. Atmos. Sci.*, **22**, 2585–2599.

Kung, R., G. Buzyna and R. L. Pfeffer, 1987: Velocity and temperature measurements with thermistor anenometers in a thermally stratified rotating fluid. *J. Phys. E. Sci. Instrum.*, **20**, 461–467.

Li, G. Q., R. Kung and R. L. Pfeffer, 1987: An experimental investigation on topographic effect on multiple regimes of baroclinic flow. *Scientia Sinica* (Series B), XXX, 83–95.

Li, G. Q., R. Kung and R. L. Pfeffer, 1988: An experimental study of baroclinic flow regimes with and without two-wave bottom topography. *Frontiers of Fluid Mechanics*, Pergamon Press.

Pfeffer, R. L., R. Kung and G. Q. Li, 1989: Topographically-forced waves in a thermally-driven rotating annulus of fluid—experiment and linear theory. *J. Atmos. Sci.*, **46**, in press.

Buzyna, G., R. L. Pfeffer and R. Kung, 1989: Kinematic properties of wave-amplitude vacillation in a thermally-driven rotating fluid. Submitted to *J. Atmos. Sci.*

Pfeffer, R. L., J. Ahlquist, R. Kung, Y. Chang and G. Q. Li, 1989: A study of baroclinic wave behavior over bottom topography using complex principal component analysis of experimental data. Submitted to *J. Atmos. Sci.*

Personnel					
	Black	Asian	Hispanic	White	Female
Faculty (7)		3	1	2	
Graduate Students (4)		4			
Undergraduate Students (30)	5	3	1	21	7
Staff (6)	1			5	3